Modeling of Concept Propulsion System

AeroPropulsoServoElasticity

Fundamental Aeronautics – Supersonics Project

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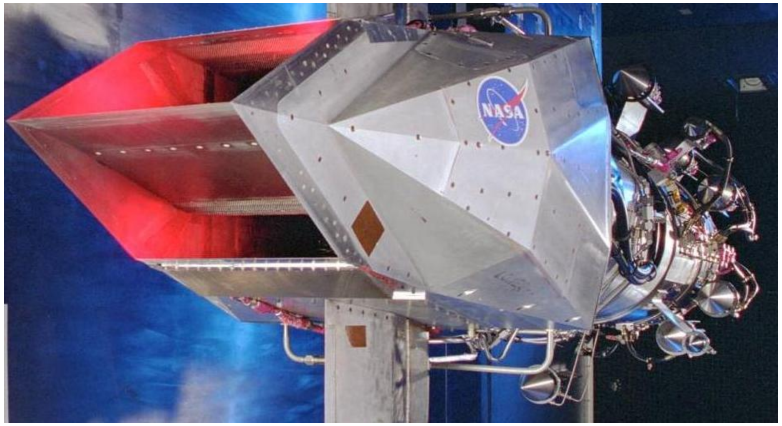
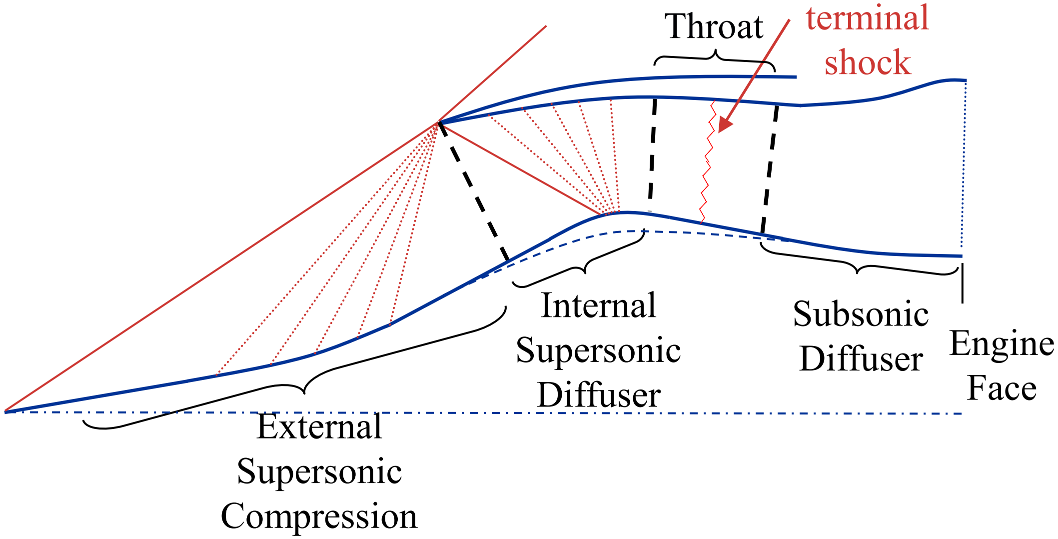
Outline

- **Supersonic Inlet modeling**
  -- Mixed Compression Inlet
  -- External Compression Inlet
- **Parallel Flow Path Modeling**
  -- Parallel Compressor Modeling
- **Engine Control Schedules**
  -- Compressor Schedule
  -- Exit Nozzle Area Schedule
- **Nozzle Modeling**
- **Variable Cycle Engine (VCE) Modeling**
- **Concluding Remarks/Future**

Supersonic Inlets Modeling

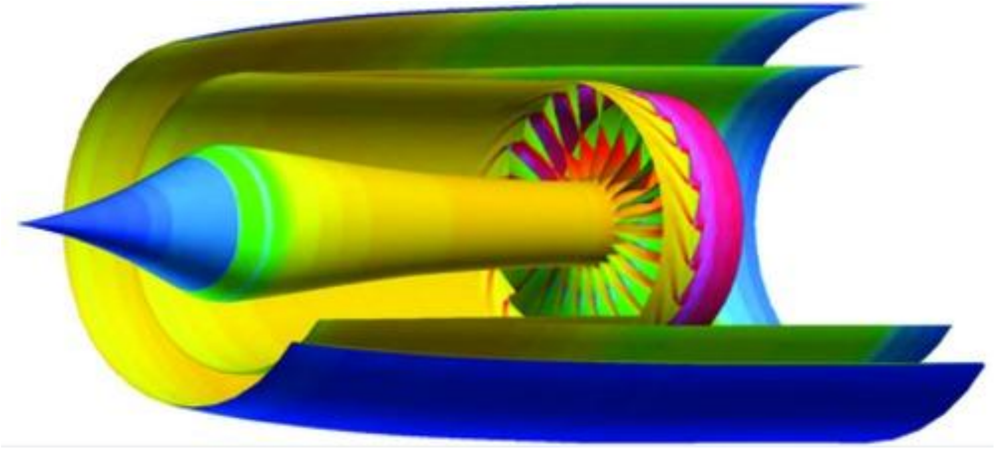
- Started with Mixed Compression Supersonic inlets

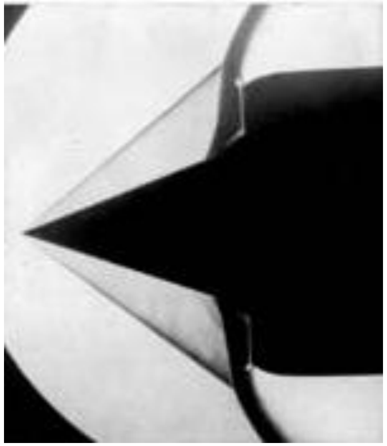




- Now focusing on external compression axisymmetric Inlets

  -- Better overall performance for Mach 1.8 or less





External Compression Modeling

- Isentropic compressible flow relations to model a system of oblique shocks (no dynamics assuming external dynamics are significantly faster than internal)

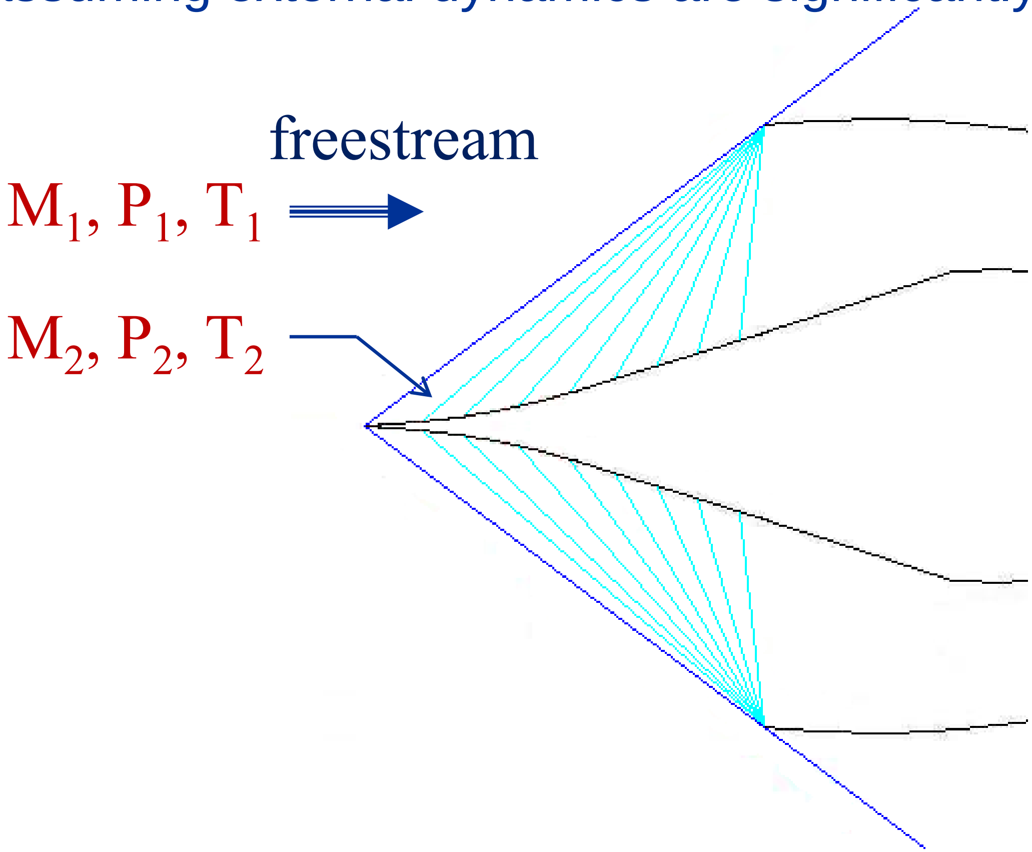
$$\tan\theta = 2\cot\beta \frac{M_{1N}^2 - 1}{M_1^2(\gamma + \cos 2\beta) + 2}$$

$$M_{1N} = M_1 \sin\beta$$

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma + 1}\left(M_{1N}^2 - 1\right)$$

$$\frac{T_2}{T_1} = \frac{P_2}{P_1}\frac{(\gamma - 1)M_{1N}^2 - 2}{(\gamma + 1)M_{1N}^2}$$

$$M_2 = \frac{1}{\sin(\beta - \theta)}\sqrt{\frac{1 + \frac{\gamma - 1}{2}M_{1N}^2}{\gamma M_{1N}^2 - \frac{\gamma - 1}{2}}}$$



- Sufficient discretization of centerbody angle (Δθ) when cowl lip conditions are not changing
- Shocks focusing at the cowl lip also verifies inlet geometry for designed condition

Internal Compression Modeling

Supersonic & Subsonic Diffusers

– Internal supersonic and subsonic compression – Quasi 1D CFD based on compressible Euler

Continuity of Mass

$$\frac{\partial \rho_s}{\partial t} = -\frac{1}{A}\frac{\partial(\rho_s A v)}{\partial x} - \frac{\rho_s}{A}\frac{\partial A}{\partial t}$$

Momentum

$$\frac{\partial}{\partial t}(\rho_s v) = -\frac{1}{A}\frac{\partial}{\partial x}[(P_s + \rho_s v^2)A] + \frac{1}{A}\left(P_s\frac{\partial A}{\partial x} - \rho_s v\frac{\partial A}{\partial t}\right)$$

Energy

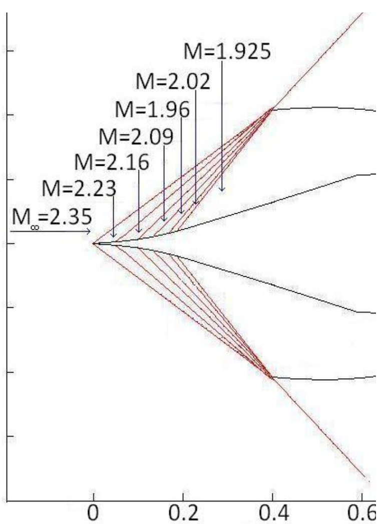
$$\frac{\partial}{\partial t}\left[\left(\frac{P_s}{\gamma-1} + \frac{\rho_s v^2}{2}\right)\right] = -\frac{1}{A}\frac{\partial}{\partial x}\left[A\left(\frac{\gamma P_s v}{\gamma-1} + \frac{\rho_s v^3}{2}\right)\right] - \frac{1}{A}\left(\frac{\gamma P_s}{\gamma-1} + \frac{\rho_s v^2}{2}\right)\frac{\partial A}{\partial t}$$

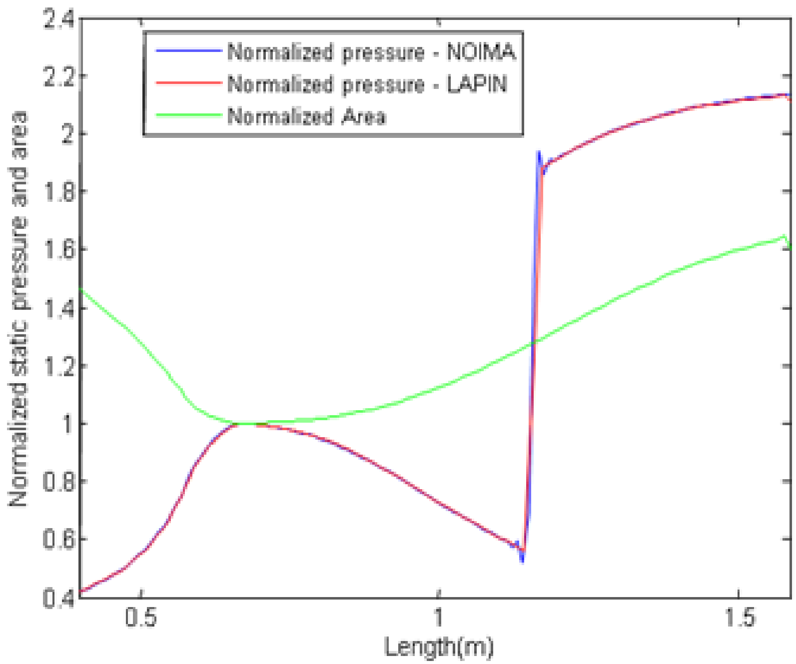
Overall CFD Equation

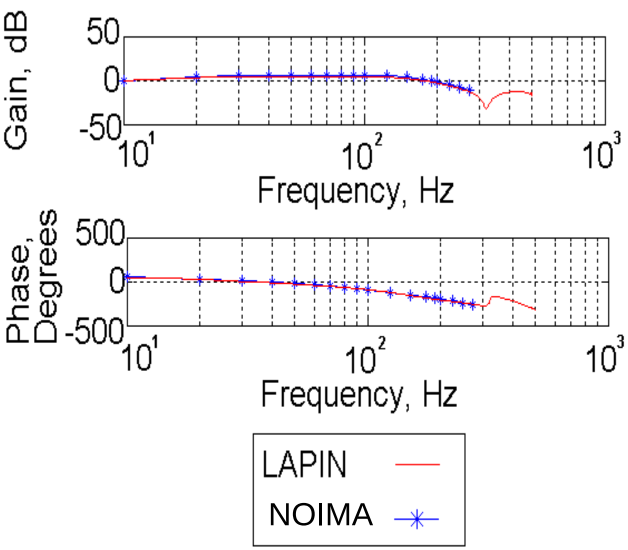
$$\frac{\partial}{\partial t}(W_{j,n}) = -\left(\frac{A_{n+1}F_{j,n+1} - A_{n-1}F_{j,n-1}}{2\Delta x A_n}\right) + \frac{S_{j,n}}{A_n} + S_v\left[\frac{(|v_n| + a_n)(A_{n+1}W_{j,n+1} - A_n W_{j,n}) - (|v_{n-1}| + a_{n-1})(A_n W_{j,n} - A_{n-1}W_{j,n-1})}{\Delta x A_n}\right]$$

Mixed Compression Inlets Modeling - Results

- New model (NOIMA) verified against legacy code named LAPIN, which was verified with testing
  - -- LAPIN written in FORTRAN (~ 80 routines), based on method of characteristics







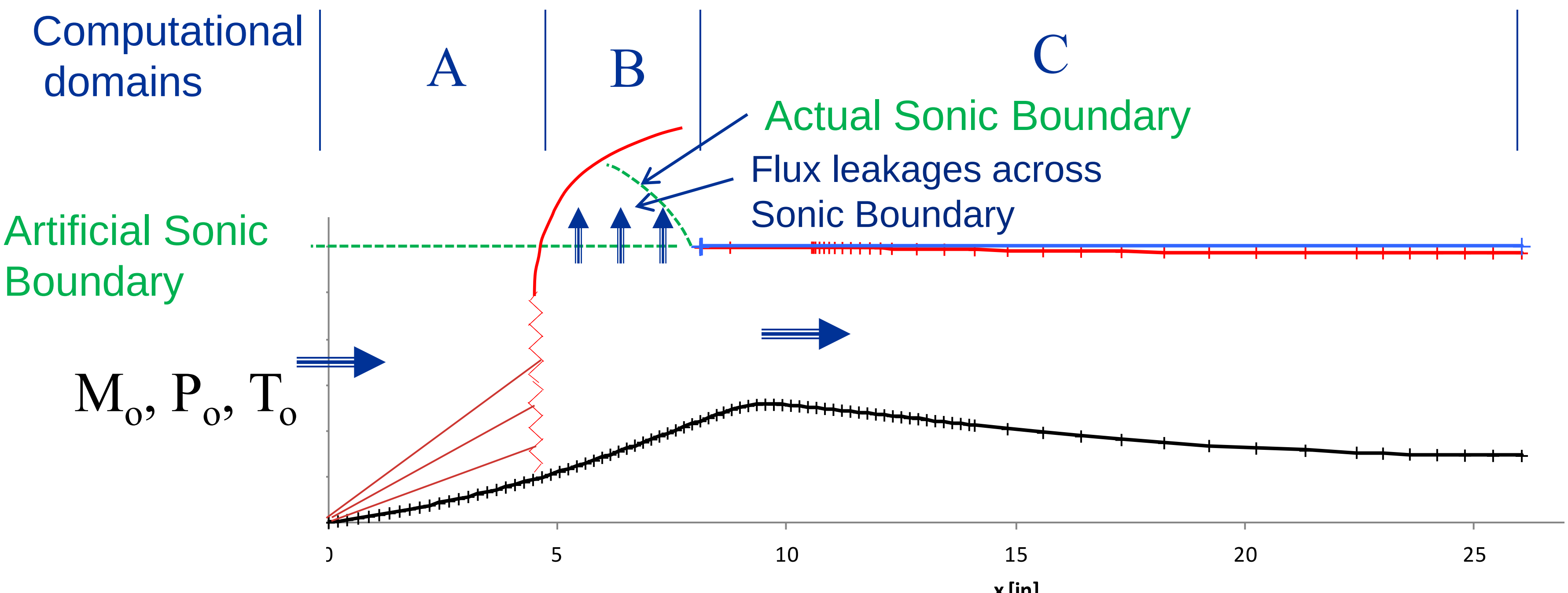
- New model can be used for controls design to increase performance and for propulsion and APSE integration

External Compression Inlet Modeling - Approach

Computational Domain

A. 1-D compressible flow cells w/ dynamics and averaging flows at shock boundary
B. Quasi 1-D CFD compressible flow cells w/ leakage fluxes estimation
C. Quasi 1-D CFD compressible flow cells

A-B. Moving computational domains



Scaled Gulfstream Inlet Geometry - tested at GRC Dec. 2010

External Compression Inlet Modeling – Challenges

Challenges

– Developing generalized formulations for conservation flux leakages across sonic boundary – Method hasn’t worked yet

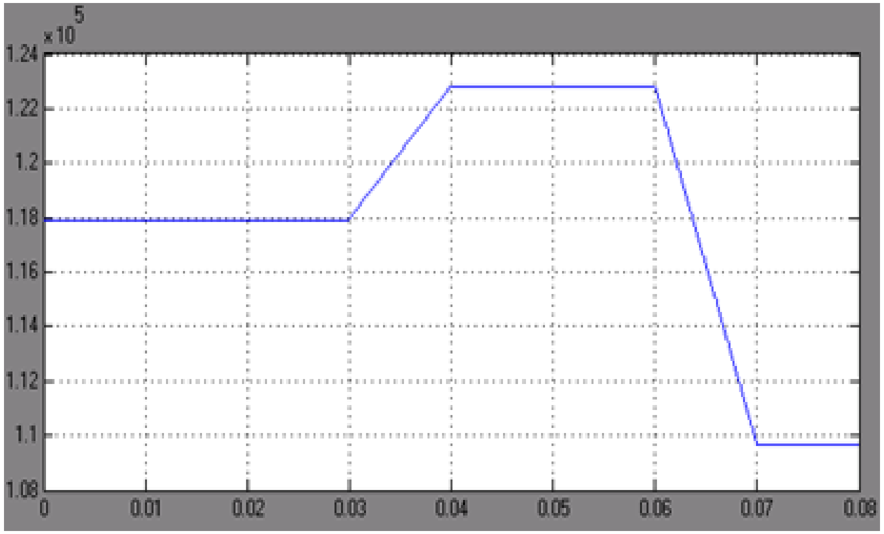
– Sensing the shock position to switch between compressible flow cells and quasi 1D CFD cells – Moving Domain

– Determined mass flow leakage based on test data for various engine face back pressures to calculate leakage fluxes – Approach worked but is not generalized

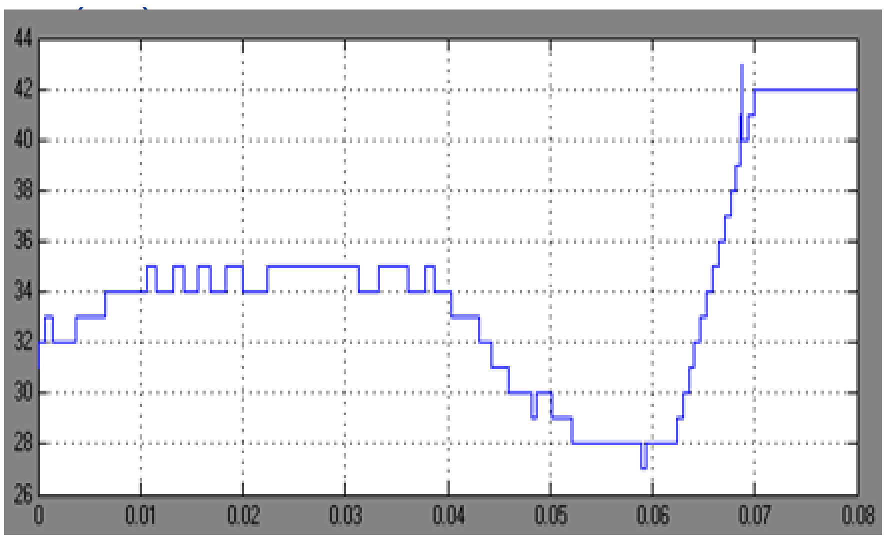
– Remaining issue for inlet dynamics Conical compressible flow field inherently 2D and 3D for pitch variations

Results – Ramping the Back Pressure

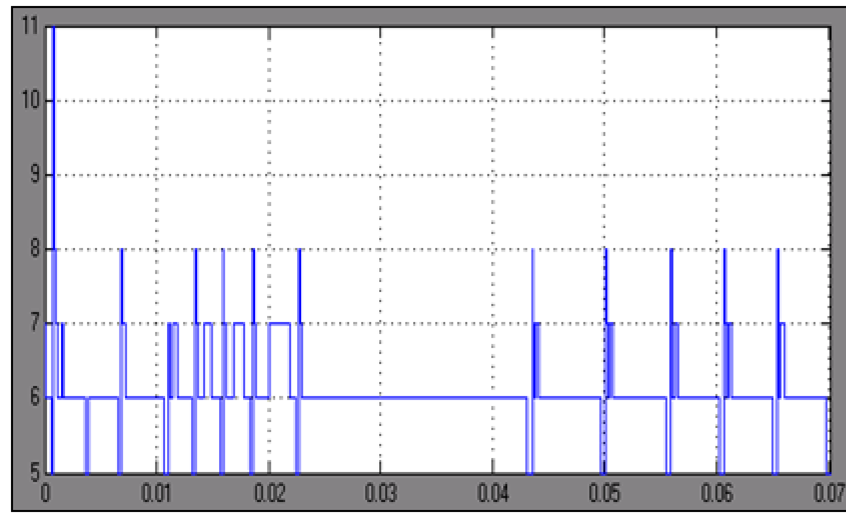
Back Pressure (N/m^2) vs. Time (sec)



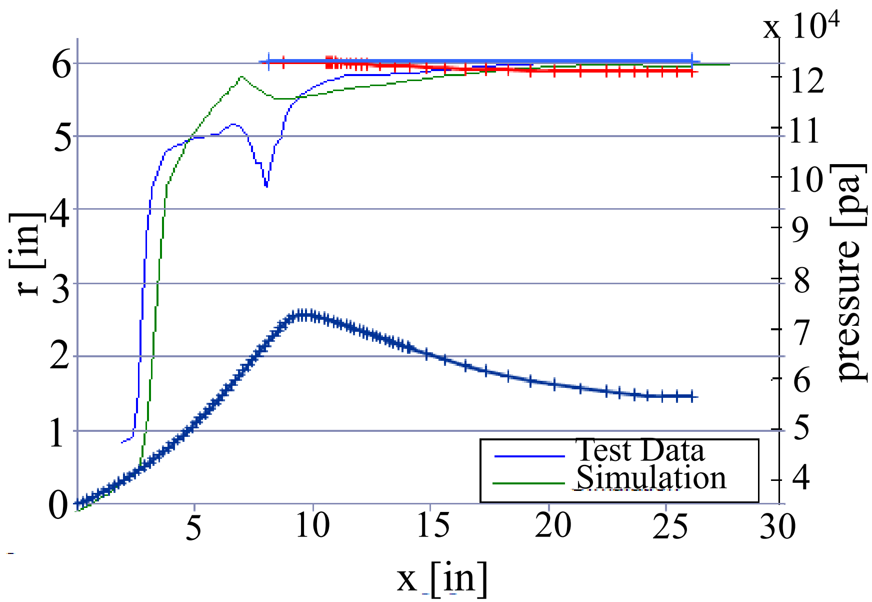
Upstream Shock Position (cell #) vs. Time



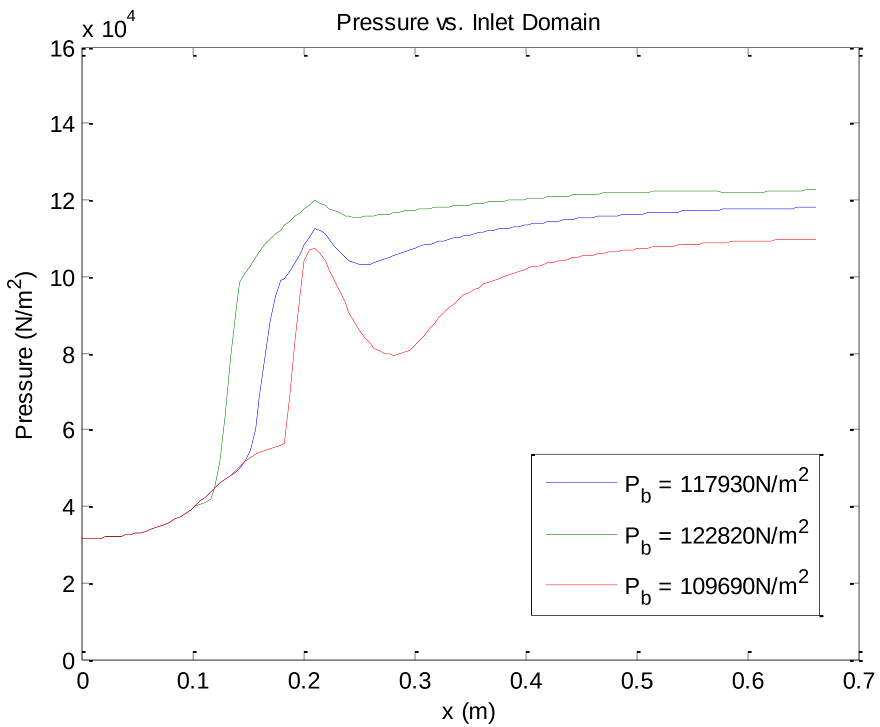
Shock Thickness (Cell) vs. Time (sec)



External Compression Inlet Results



Comparing test and Simulation Results



Pressure profile by ramping back pressure

Difference In Shock Position

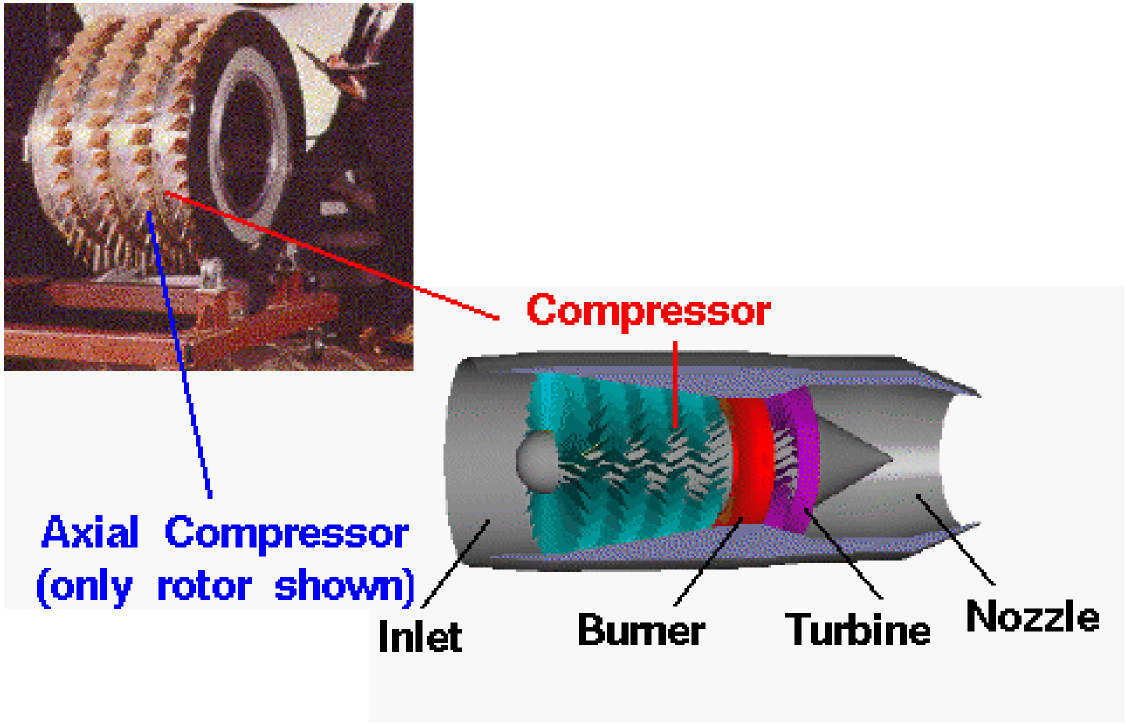
Back Pressure (N/m^2)	Test Data Shock Position (Cell)	Simulation Shock Position (Cell)
109690	41	42
117930	32	34-35
122820	26	28

Parallel Compressor Modeling

Objective

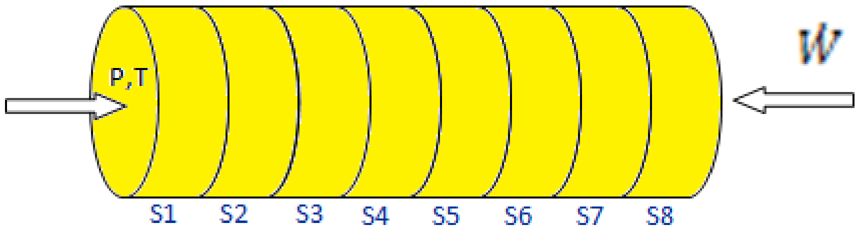
– Develop parallel flow path models of propulsion components to study effect of distortion on propulsion system dynamics and APSE

– First step in the process: develop compressor model with parallel flow paths

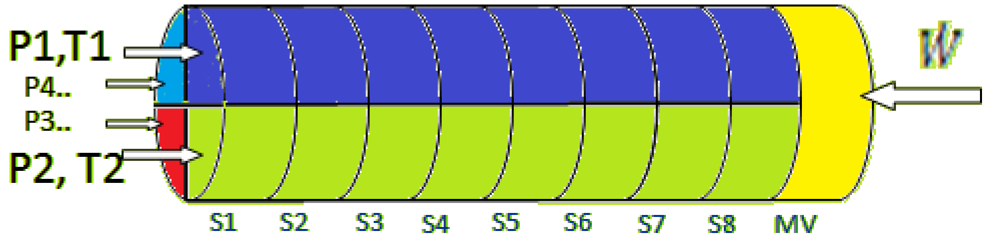


Overview

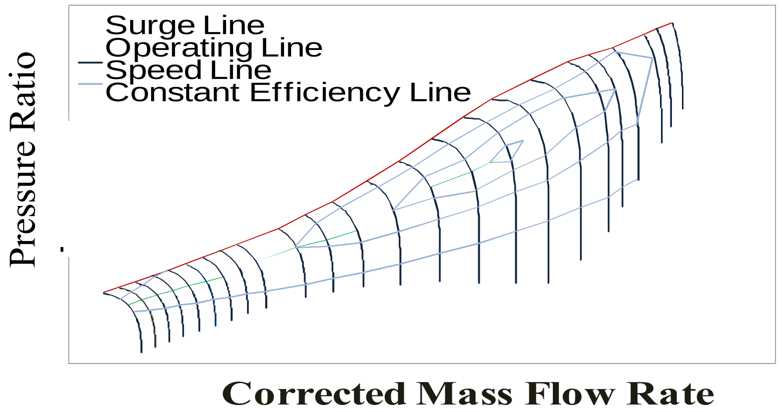
- New model derived in cylindrical coordinates - Euler
- Allows modeling of disturbance from changing flight conditions (pitch, yaw, roll, etc)
- Inlet conditions of Pressure, Temperature & outlet conditions of mass flow rate
- Path ratio of β_i - adjusting mass flow rate of stage maps by path ratio



Original model
Stage-by-stage, single flow path



New Model - Multiple Interacting Flow Paths



Parallel Compressor Modeling Approach

Conservation Dynamics in 2D Cylindrical Coordinates

- Equations were derived in cylindrical coordinates for compressible & inviscid flow, assuming flow properties do not vary in the radial direction

Conservation Equations $\frac{\partial}{\partial t}(W_j) = -a_{xj}\frac{\partial}{\partial x}(F_{xj}) - a_{\varphi j}\frac{\partial}{\partial \varphi}(F_{\varphi j}) + S_j$

j	Wj	Fxj	Fφj	Sj	a_{xj}	$a_{\phi j}$
1	ρ_s	$\rho_s u$	$\rho_s w$	0	1	$\frac{1}{r}$
2	$\rho_s u$	$\rho_s u$	$\rho_s u$	$-\frac{\partial P_s}{\partial x}$	u	$\frac{w}{r}$
3	$\rho_s w$	$\rho_s w$	$\rho_s w$	$-\frac{1}{r}\frac{\partial P_s}{\partial \varphi}$	u	$\frac{w}{r}$
4	$\frac{P_s}{\gamma-1}+\frac{\rho_s V^2}{2}$	$\frac{\gamma P_s u}{\gamma-1}+\frac{\rho_s u^3}{2}$	$\frac{\gamma P_s w}{\gamma-1}+\frac{\rho_s w^3}{2}$	0	1	$\frac{1}{r}$

$$\frac{\partial}{\partial t}(W_{j,n,m}) = -a_{xj,n,m}\left(\frac{F_{xj,n+1,m} - F_{xj,n,m}}{\Delta x}\right) - a_{\varphi j,n,m}\left(\frac{F_{\varphi j,n,m+1} - F_{\varphi j,n,m-1}}{2\Delta\varphi}\right) + \frac{S_{j,n,m-1} - S_{j,n,m+1}}{2s}$$

Parallel Compressor Modeling Approach

Mixing volume - weighted average of pressure, temperature outputs from compressor stages

Mixing Volume Equations

Momentum:

$$\frac{\partial}{\partial t}\dot{W}_{mv} = \frac{A_{mv}g}{l_{mv}}\left[\sum_{j=1}^{m}\left(\beta_j P_{tj,i=n}\right) - P_{t,mv}\right]\left(1 + \frac{\gamma_{cp}-1}{2}M_{mv}^2\right)^{-\frac{\gamma_{cp}}{\gamma_{cp}-1}}$$

Continuity:

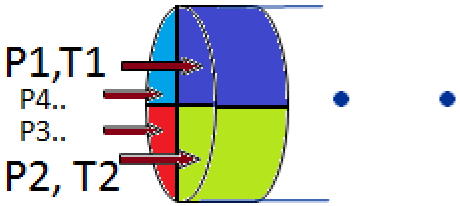
$$\frac{\partial}{\partial t}\rho_{s,mv} = \frac{1}{V_{mv}}\left(\dot{W}_{mv} - \dot{W}_{cb}\right)$$

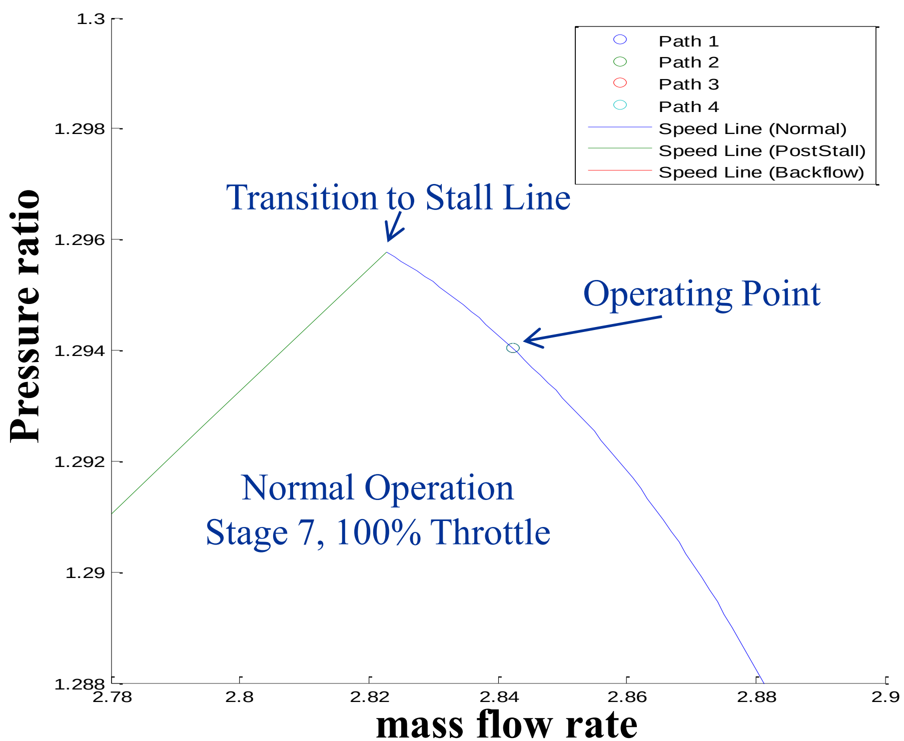
Energy:

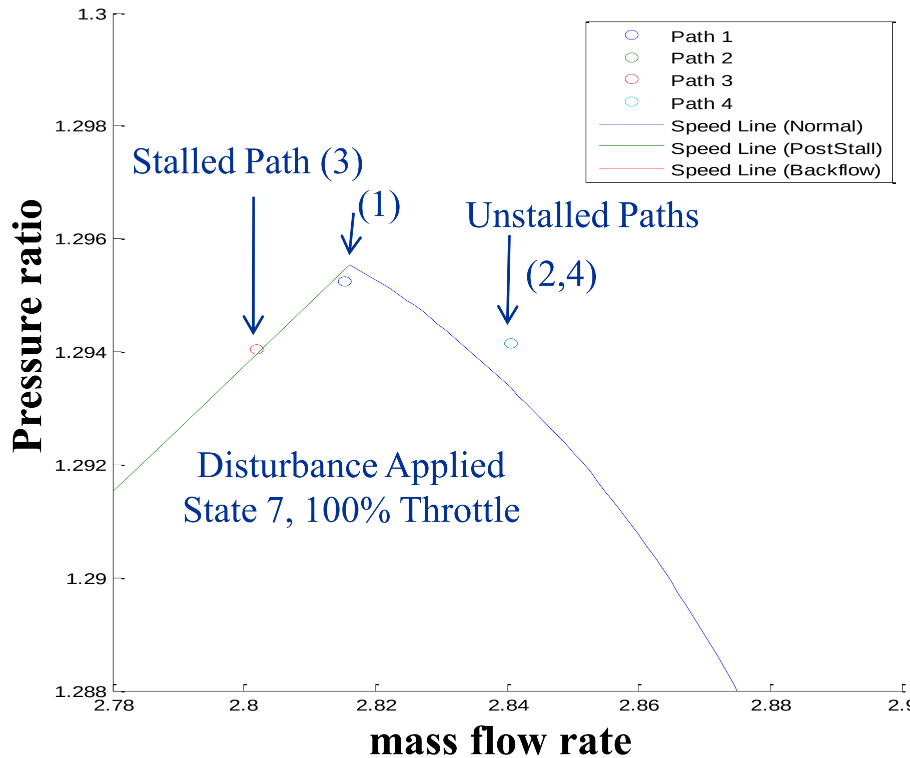
$$\frac{\partial}{\partial t}\rho_{s,mv}T_{t,mv} = \frac{\gamma_{mv}}{V_{mv}}\left[\dot{W}_{mv}\sum_{j=1}^{m}\left(\beta_j^2 T_{tj,i=n}\right) - \dot{W}_{cb}T_{t,mv}\right]$$

Parallel Compressor Modeling Results

- Pressure distortion of approximately 0.1% applied to path 1



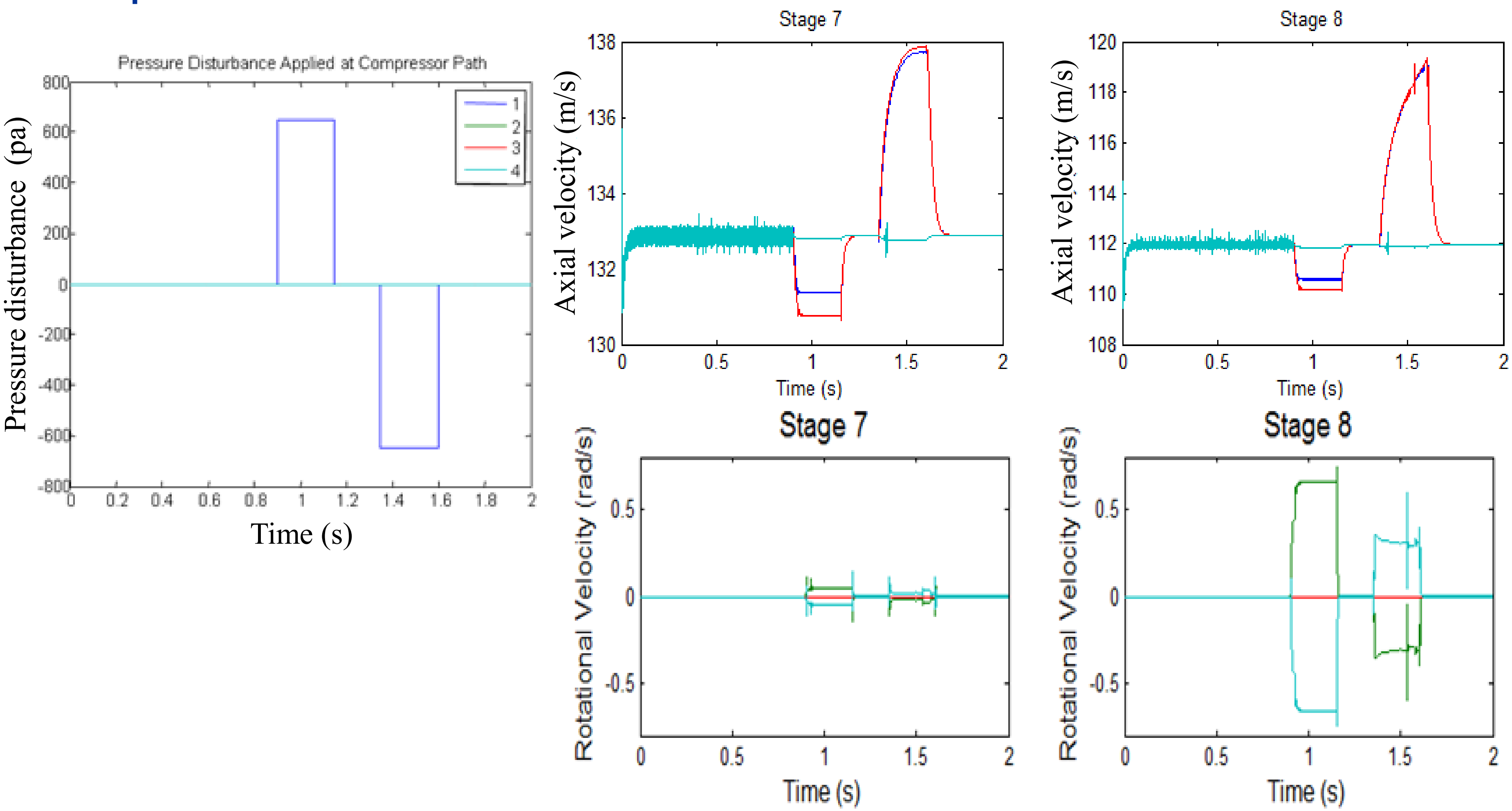




- Pressure disturbance moves Path 1, Path 3 operating points to surge line
- Would experience cascading stall if mass flow rate was not held constant (as with engine)

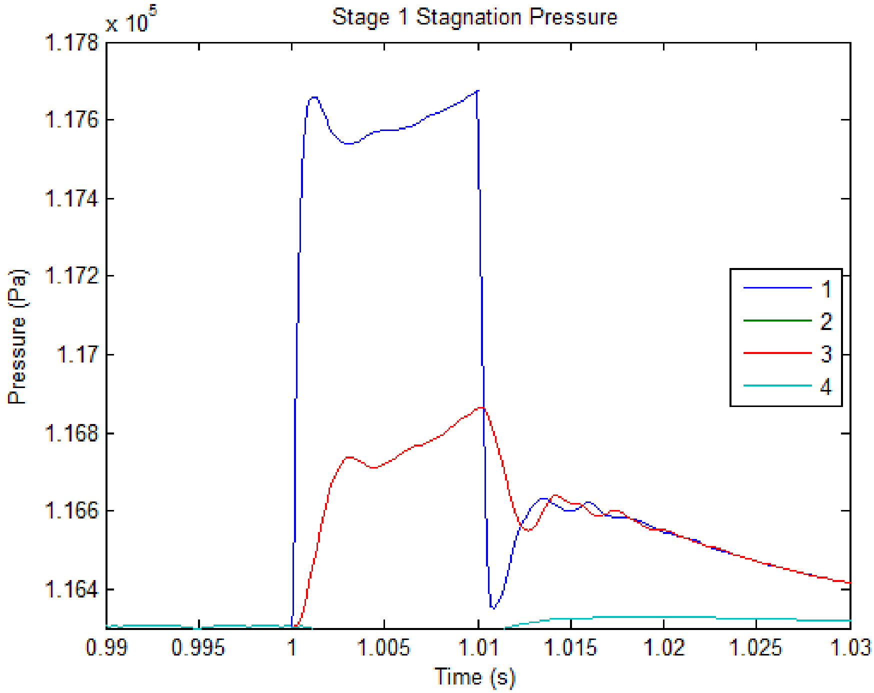
Parallel Compressor Modeling Results

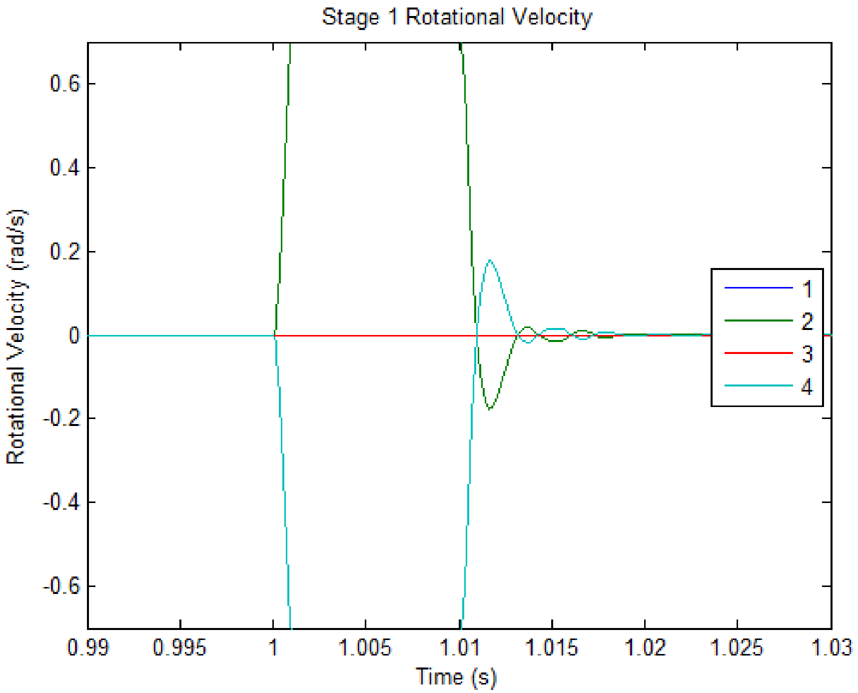
- Square wave distortion applied to compressor input, path 1



- Pulsating effect of rotational velocity from one stage to the next

Parallel Compressor Modeling Results

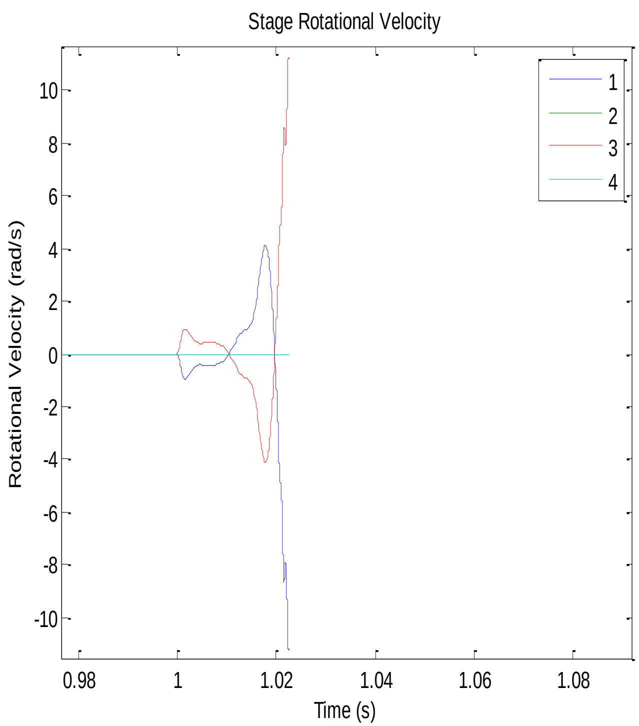


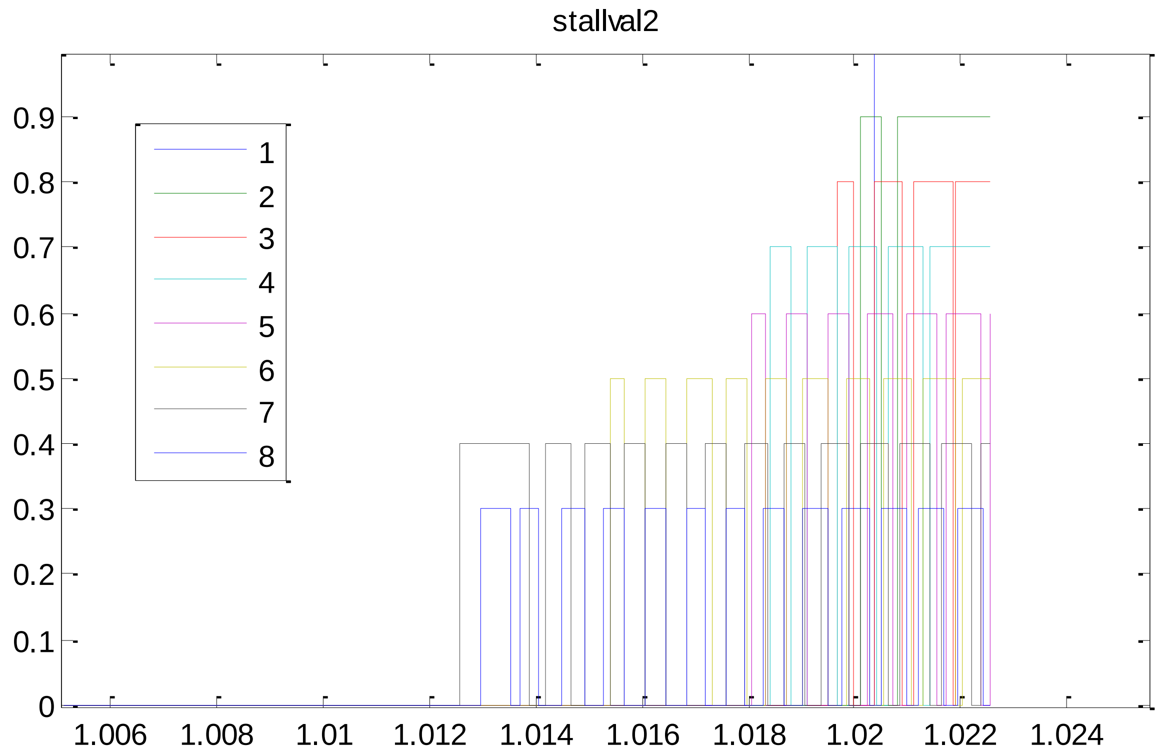


- Distortion with shorter duration applied (larger amplitude about 0.2%)
- Different disturbance frequencies produce different distortion patterns (different frequency domain response)

Parallel Compressor Modeling Results

1st Stage at 100% Speed w/ 1300pa (0.16%) Distortion on Sector 2 & 4



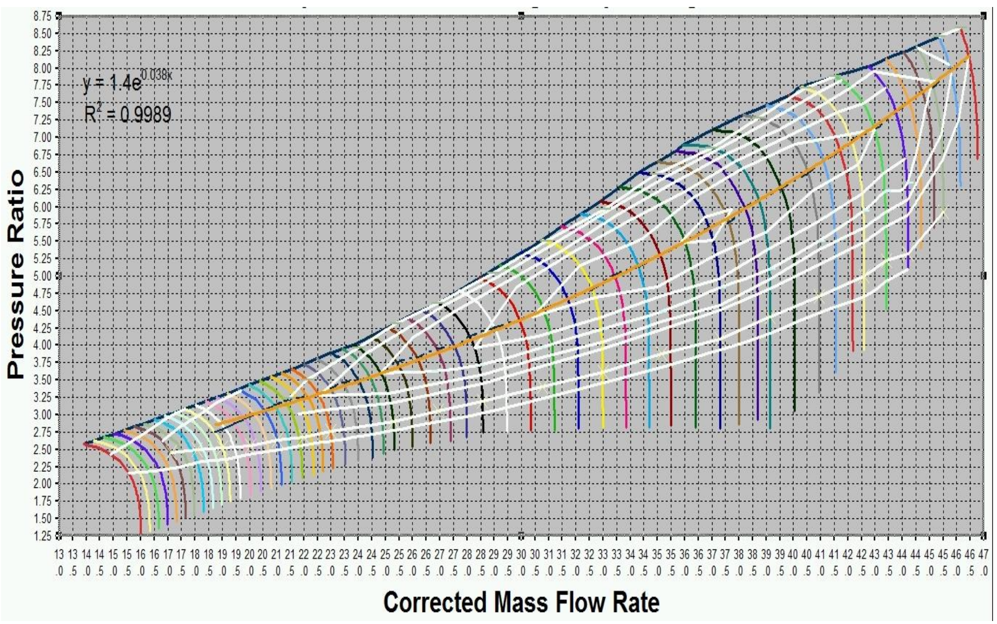


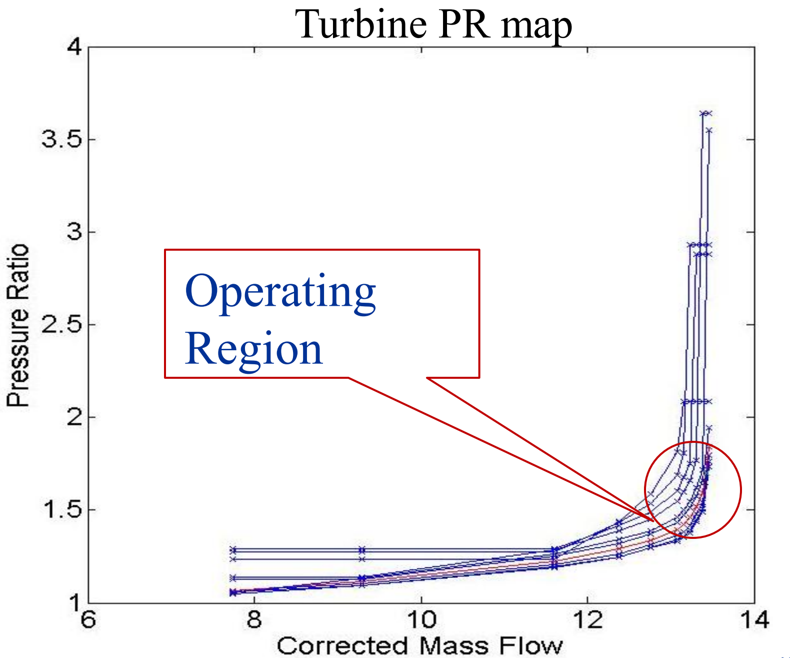
Stall Pattern – From Back to Front of Compressor

(0 Normal, > 0 Stall)

Engine Operating Schedules

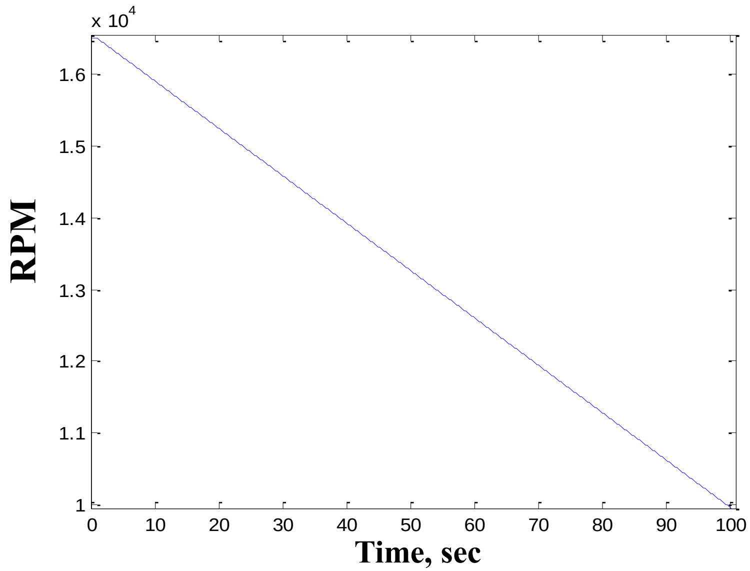
- Prior (2009 WS) compressor operating schedule derivation approach developed for full speed envelope operation – used generic maps
  - -- Developed a bleed schedule – Info on Inlet Guide Vane (IGV) not available
  - -- First derived schedule utilizing isolated compressor model
  - -- Integrated w/ engine: could not maintain original operating line & turbine unchoked – compressor/turbine performance not exactly matched.
  - -- Corrected by rescaling turbine maps



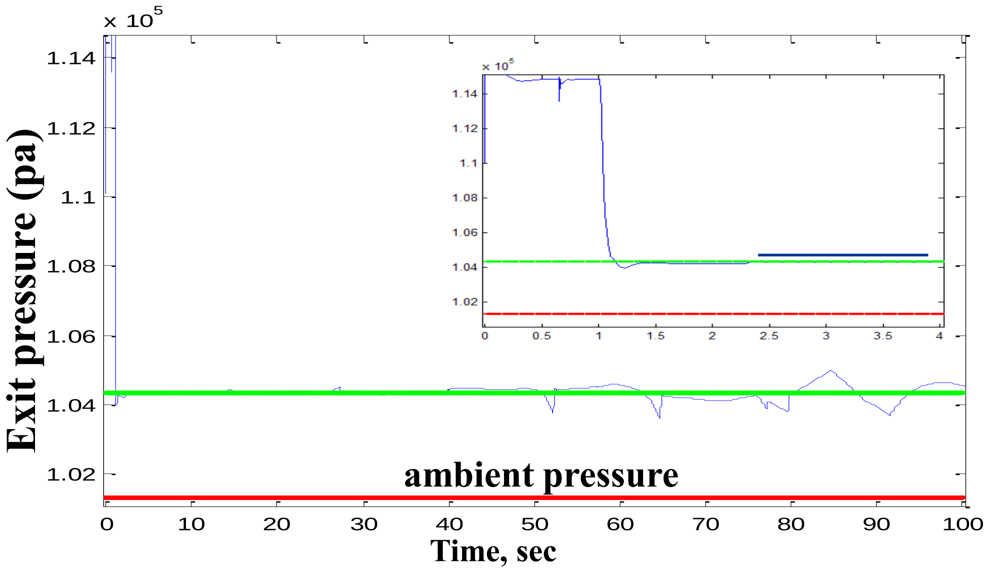


Exit Nozzle Area Schedule

- Developed exit nozzle area schedule approach – Objective to fully expand flow at nozzle exit
  - -- Approach based on PR vs. Cd (flow discharge coefficient) schedule & area limit vs. speed
  - -- Creates feedback system w/ instabilities – Designed Notch filters to stabilize system
  - -- System sensitive to unmatched compressor/turbine – required rescaling



Engine Speed (100% to 60%)



Exit Nozzle Pressure as Speed Decreases Starting from 100%

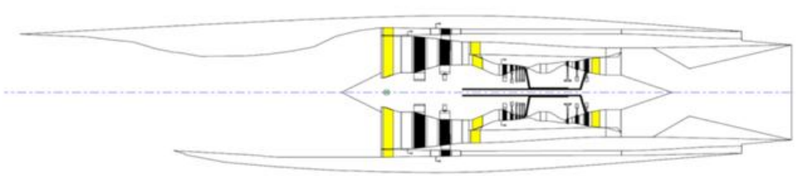
Nozzle Modeling

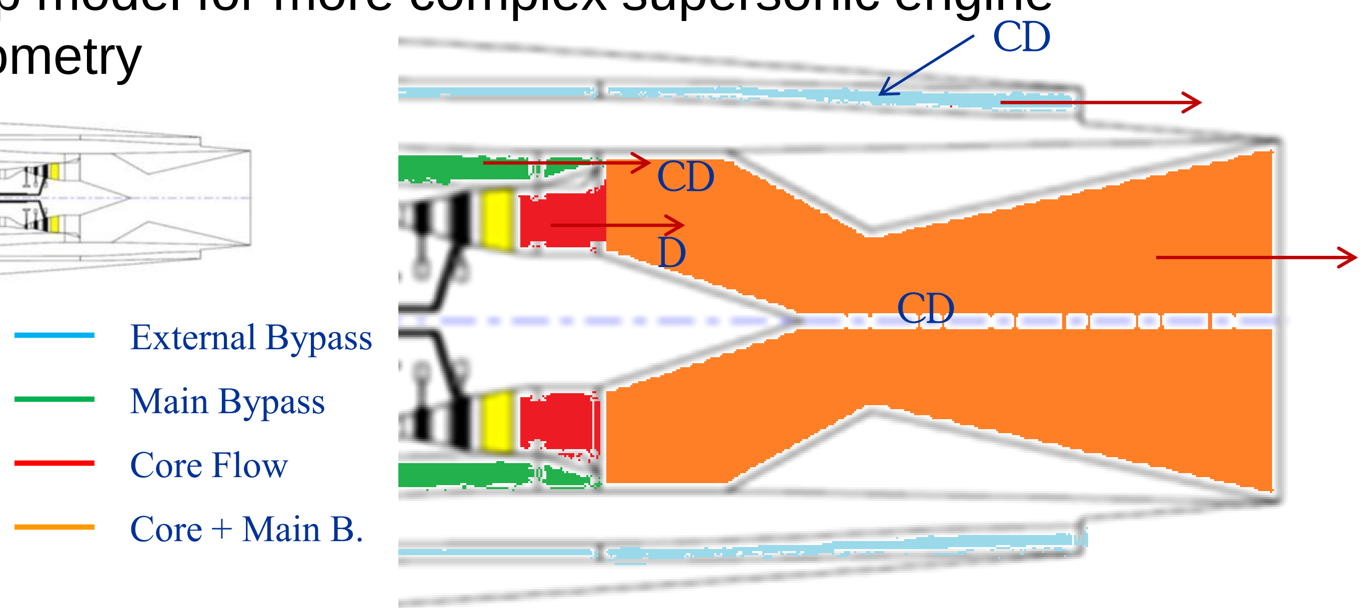
Objective/Approach

- Develop 1D CFD model for exit nozzles for thrust dynamics (before used nozzle lump volume and chocked compressible flow function)
  - -- Chosen method: MacCormack’s predictor-corrector technique assuming subsonic-supersonic isentropic nozzle flow

- **Step one** - develop model for generic Convergent-Divergent (CD) nozzle geometry

- **Step two** – develop model for more complex supersonic engine-nozzle concept geometry

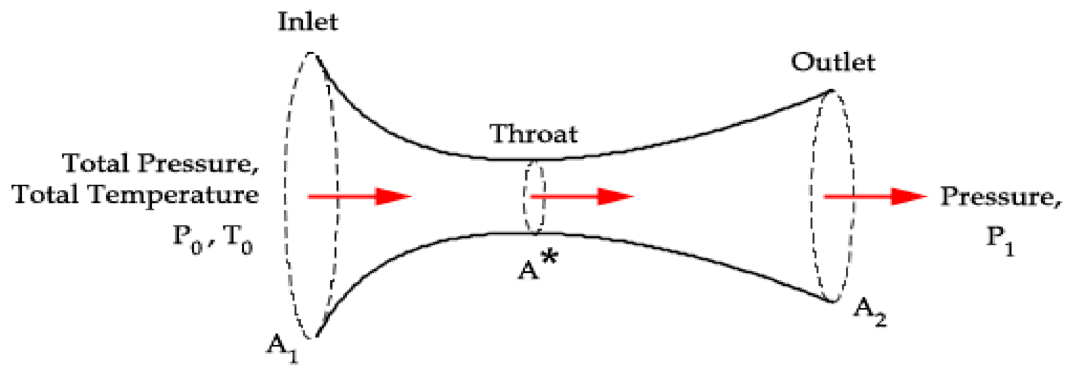


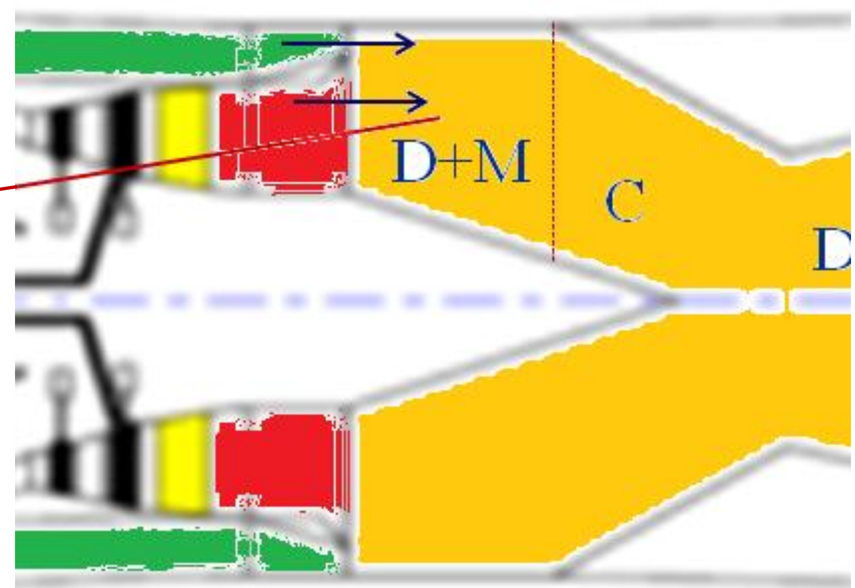


Nozzle Modeling

Converging-Diverging Nozzle

- Throat and Exit Areas used from N+3 engine simulation
- Used simple shape profile – actual N+3 nozzle profile not known
- Implemented MacCormack's method - variable area to be implemented in formulations
- Some 2D may need to be done
- For propulsion system exit nozzle area schedules need to be developed





CFD Method- Predictor Step

Predictor

$$\left(\frac{\partial \rho}{\partial t}\right)_i^t = -\frac{1}{A}\rho_i^t u_i^t \left(\frac{A_{i+1} - A_i}{\Delta x}\right) - u_i^t \left(\frac{\rho_{i+1} - \rho_i}{\Delta x}\right) - \rho_i^t \left(\frac{u_{i+1} - u_i}{\Delta x}\right)$$

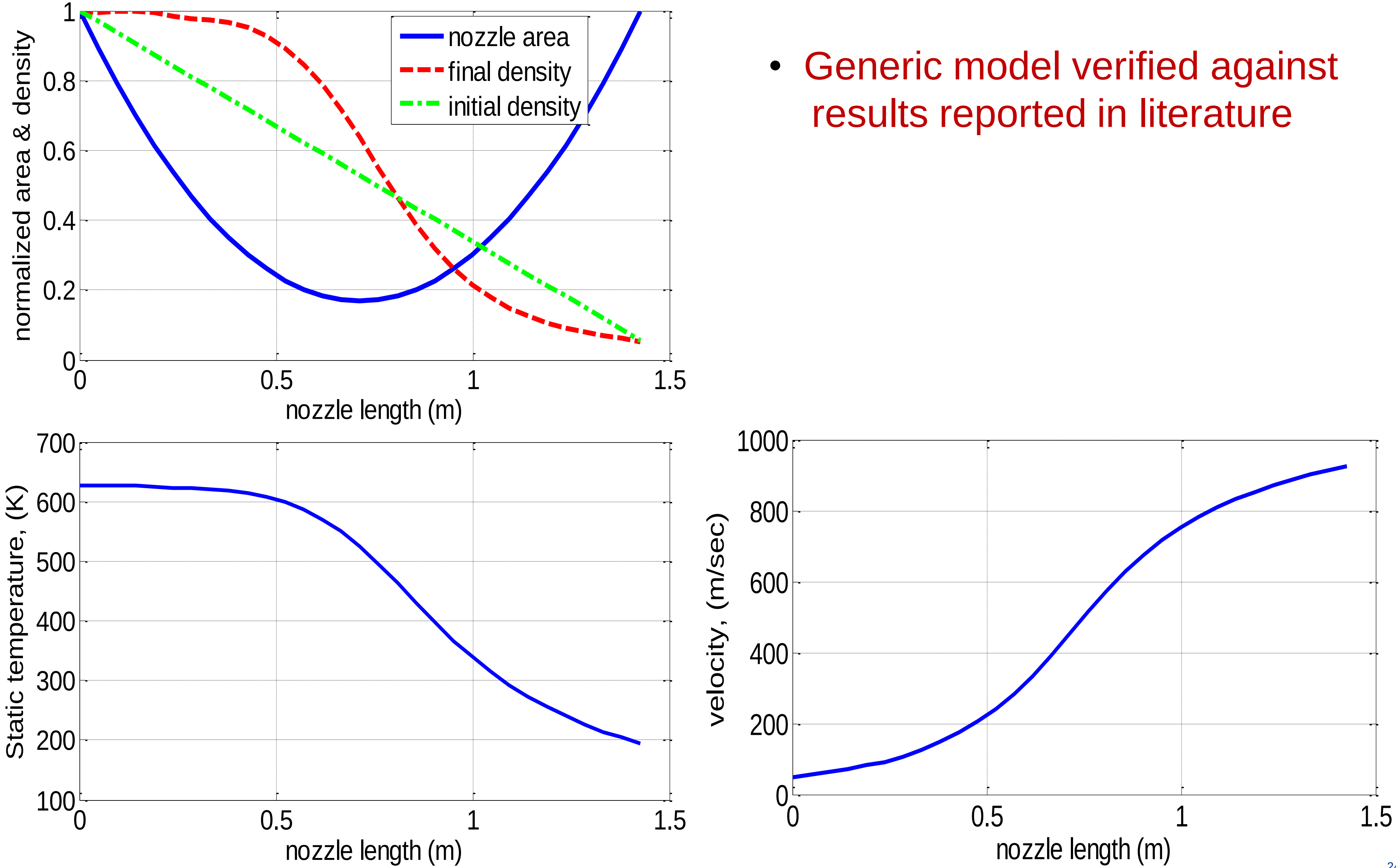
$$\bar{\rho}_i^{t+\Delta t} = \rho_i^t + \left(\frac{\partial \rho}{\partial t}\right)_i^t \Delta t$$

Corrector

$$\overline{\left(\frac{\partial \rho}{\partial t}\right)}_i^{t+\Delta t} = -\frac{1}{A}\rho_i^{t+\Delta t} u_i^{t+\Delta t} \left(\frac{A_i - A_{i-1}}{\Delta x}\right) - u_i^{t+\Delta t} \left(\frac{\rho_i^{t+\Delta t} - \rho_{i-1}^t}{\Delta x}\right) - \rho_i^t \left(\frac{u_i^{t+\Delta t} - u_{i-1}^t}{\Delta x}\right)$$

$$\rho_i^{t+\Delta t} = \rho_i^t + \frac{1}{2}\left[\left(\frac{\partial \rho}{\partial t}\right)_i^t + \overline{\left(\frac{\partial \rho}{\partial t}\right)}_i^{t+\Delta t}\right] \Delta t$$

Results
(so far steady state – no freq responses)



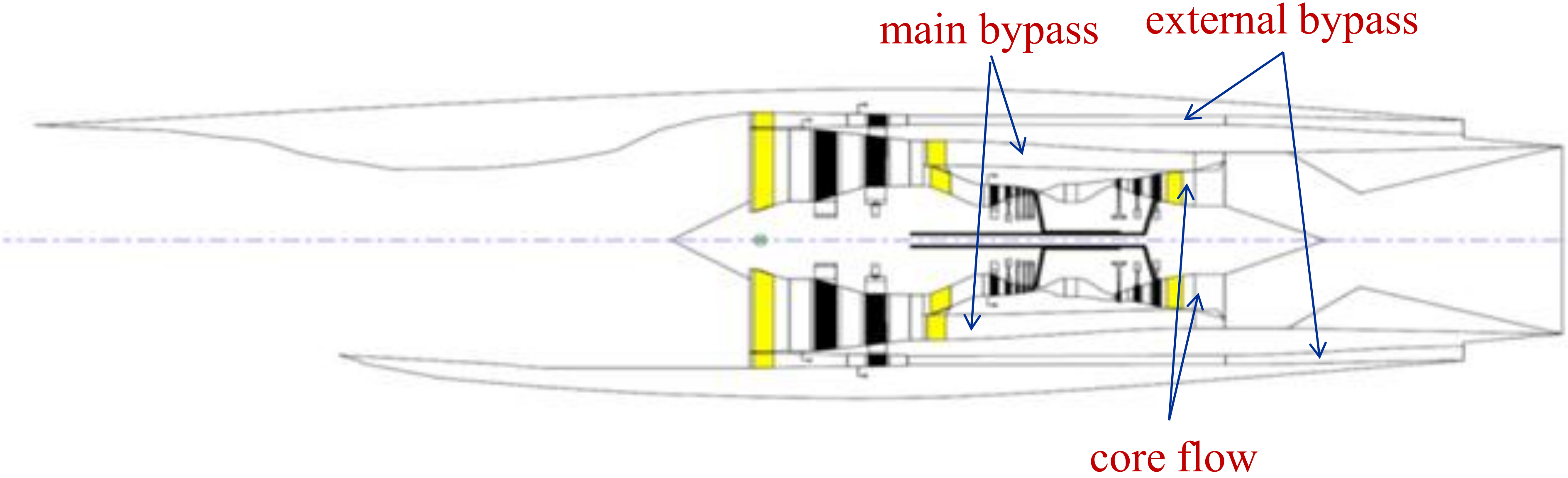
- Generic model verified against results reported in literature

Variable Cycle Engine Model

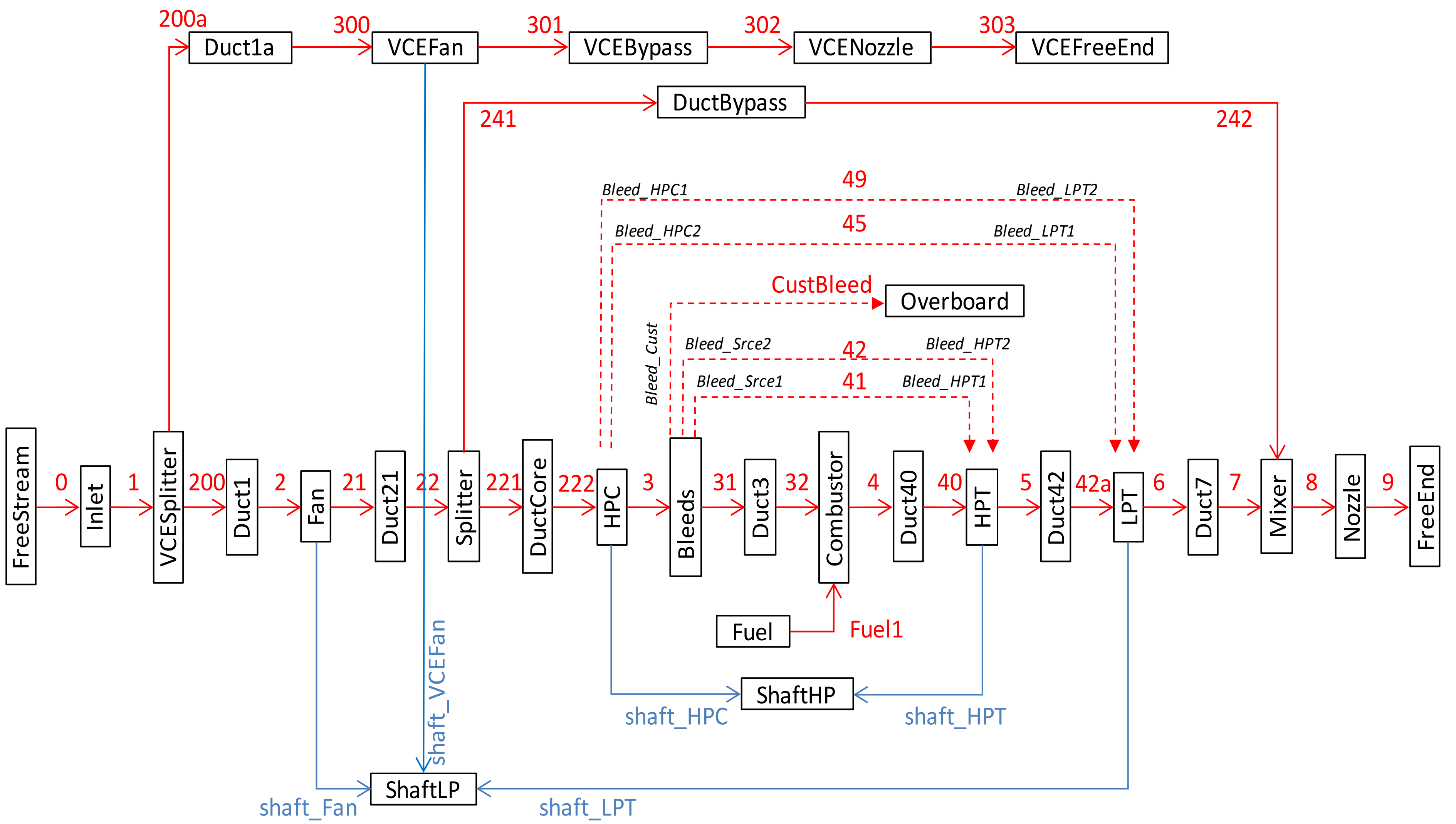
- Dual Spool variable cycle – High bypass at low altitudes to low bypass high altitudes

- Noise abatement for overland flight
  -- Through external bypass & through nozzle design

- Cycle analysis conducted in NPSS – provided geometries and component performance characteristics for dynamic model



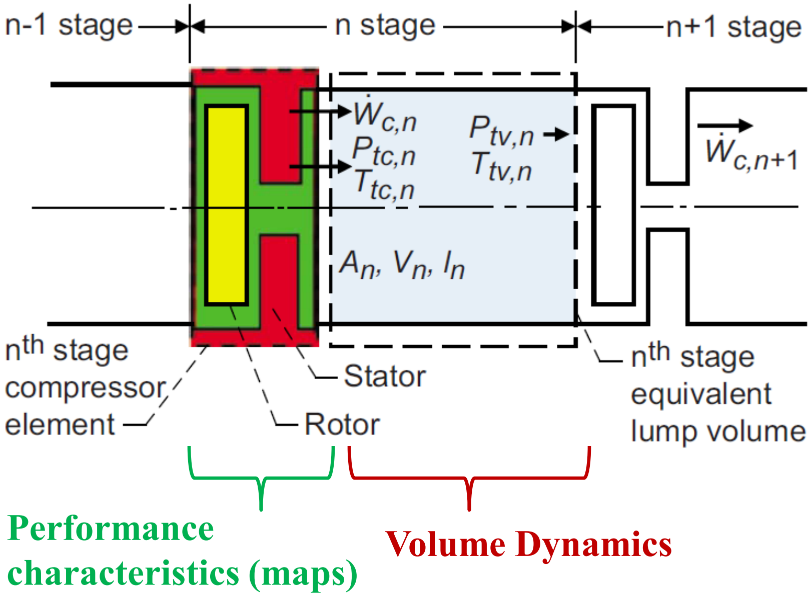
Variable Cycle Engine Model Components



Component Modeling - Roadmap & Approach

Development Roadmap

1. Original component models developed based on J85-13 engine
2. Many of J85-13 component models directly utilized for VCE w/ the appropriate maps and geometries
3. Some new component models developed (ducts, mixers, splinters, dual core) - **VCE V.1**
4. For some components need to develop detailed models – like CFD for inlet & nozzles
5. Need to develop fully operational engine (control schedules) – Methodology developed w/ J85-13
6. Parallel flow paths for distortion & boundary layer effects
7. Propulsion & ASE integration – Interfaces and controls



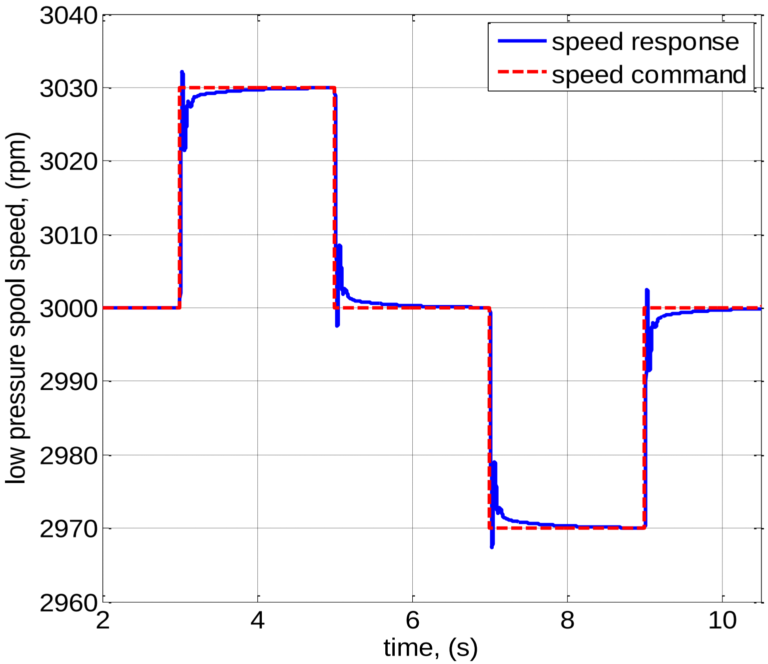
Continuity of mass, momentum & energy

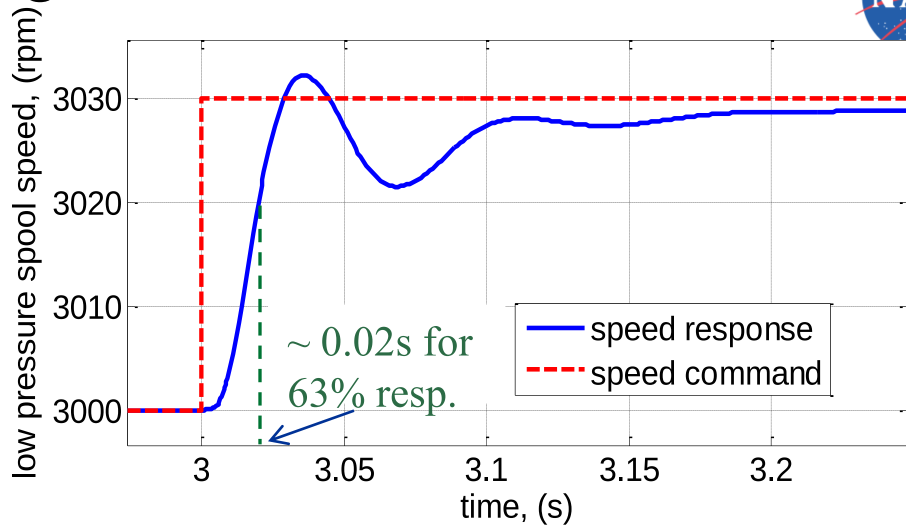
$$\frac{d}{dt}\rho_{\mathrm{sv},n} = \frac{1}{V_n}(\dot{W}_{c,n} - \dot{W}_{c,n+1} - \dot{W}_{b,n})$$

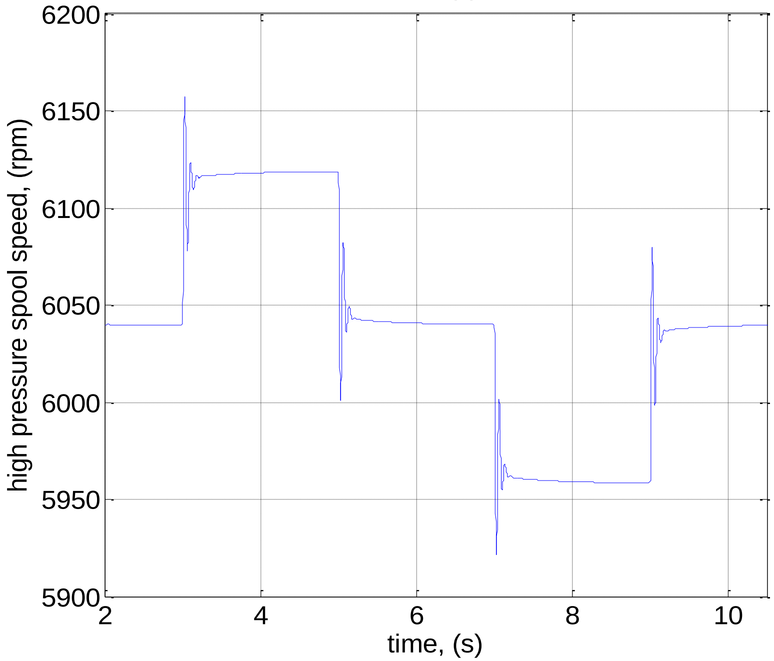
$$\frac{d}{dt}\dot{W}_{c,n} = \frac{A_n g}{l_n}(P_{\mathrm{tc},n} - P_{\mathrm{tv},n})\left(1 + \frac{\gamma_{\mathrm{cp}} - 1}{2}M_n^2\right)^{-\gamma_{\mathrm{cp}}/(\gamma_{\mathrm{cp}}-1)}$$

$$\frac{d}{dt}(\rho_{\mathrm{sv},n}, T_{\mathrm{tv},n}) = \frac{\gamma_{\mathrm{cp}}}{V_n}(T_{\mathrm{tc},n}\dot{W}_{c,n} - T_{\mathrm{tv},n}\dot{W}_{c,n+1} - T_{\mathrm{tv},n}\dot{W}_{b,n})$$

VCE Engine Results



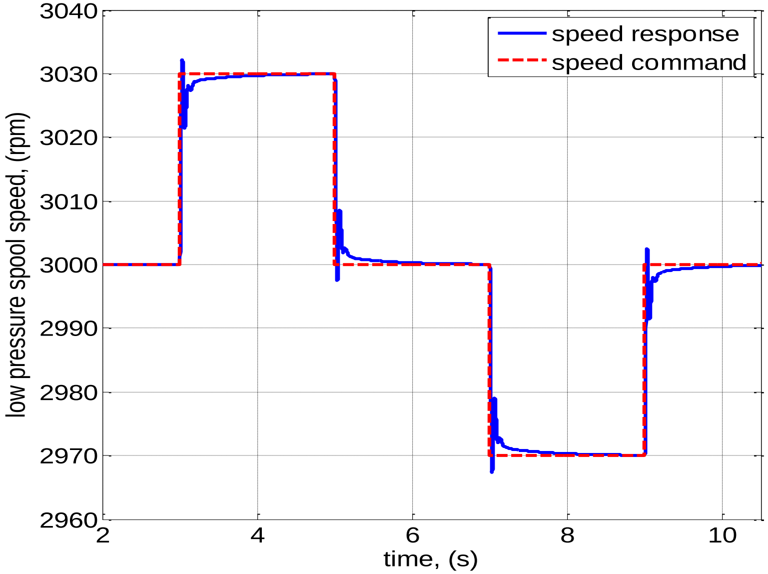


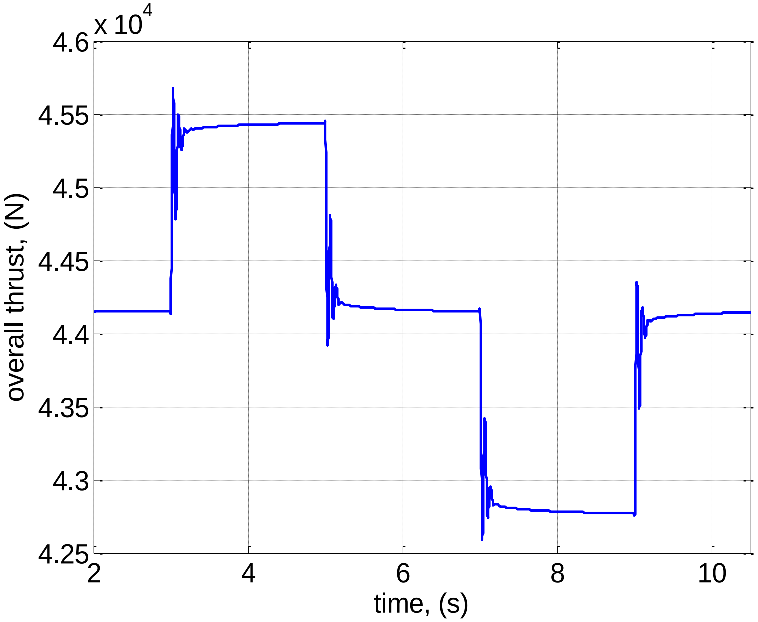


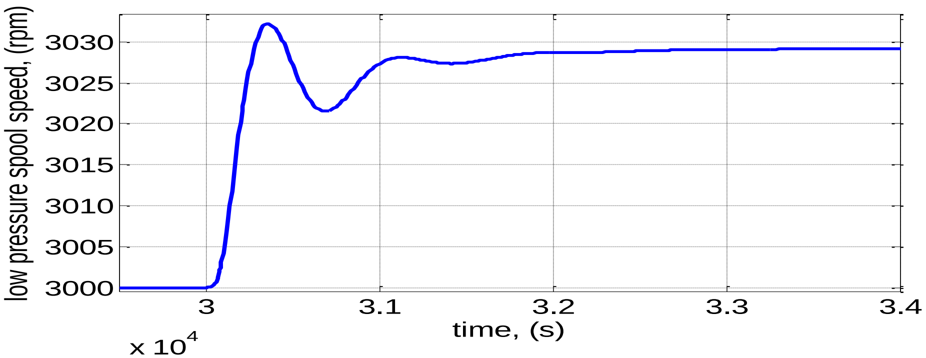
<u>Initial objective is VCE model development</u>

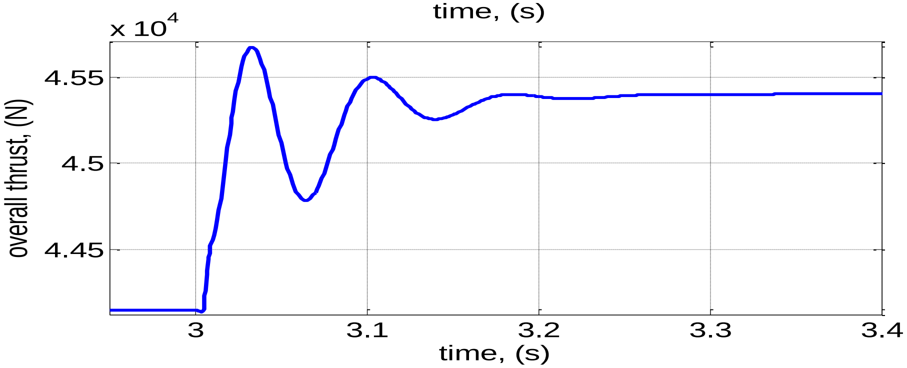
- Control design effort light; hold model together
  - -- But designed for higher bandwidth controls for disturbance attenuation
- Engine has higher response capability of ~ 70 rad/sec on high side (~40 rad/sec typically used)
- Potential to use higher response capability to design for better disturbance attenuation, safety margins, and engine efficiency

VCE Engine Speed and Thrust









- Nominal VCE propulsion system thrust 44,100 N or 9,914 lbf
- A 1% change in fan speed causes 2.9% change in thrust
- Thrust response more underdamped – design of speed controller also needs to consider thrust response

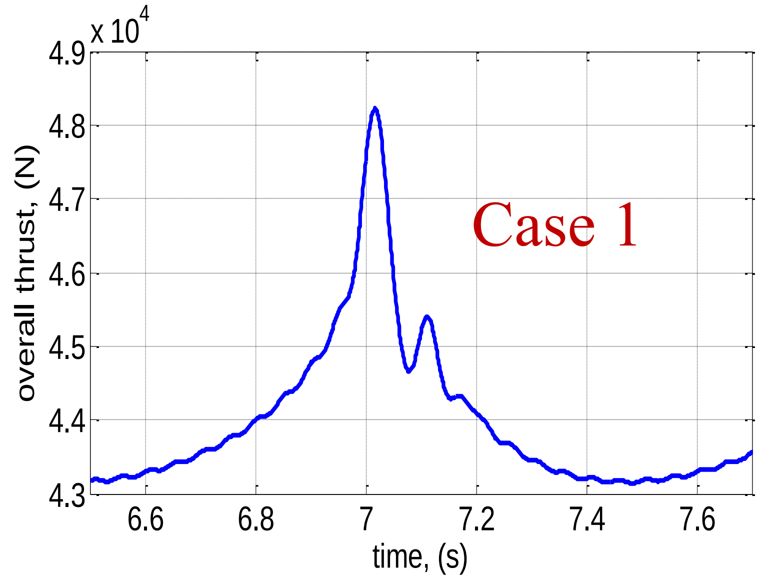
VCE Engine Atmospheric Disturbance and Thrust

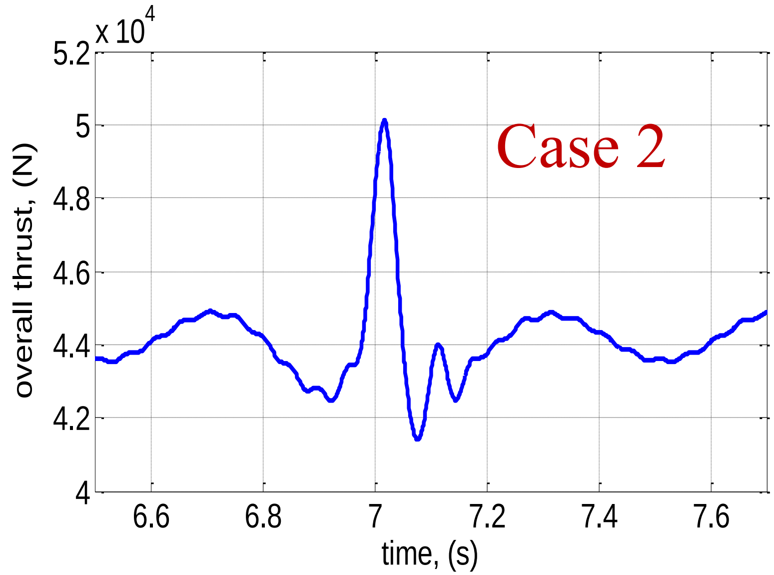
Thrust response w/ Atmospheric Disturbance

With no external compression inlet & no 1D CFD for nozzles

- Case 1; **eddy dissipation rate** 4x average of North Atlantic cruise altitudes; **integral length scale** typical (equivalent to atmospheric turbulence patch size of ~ 11 km); **max locally dissipating wind speeds** 80 mph
  -- Results in thrust variations up to ~ 5000 N or 1124 lb

- Case 2; eddy dissipation rate worst recorded; integral length scale typical; max dissipating wind speeds 150 mph
  -- Results in thrust variation up to ~ 9000N or 2024lb

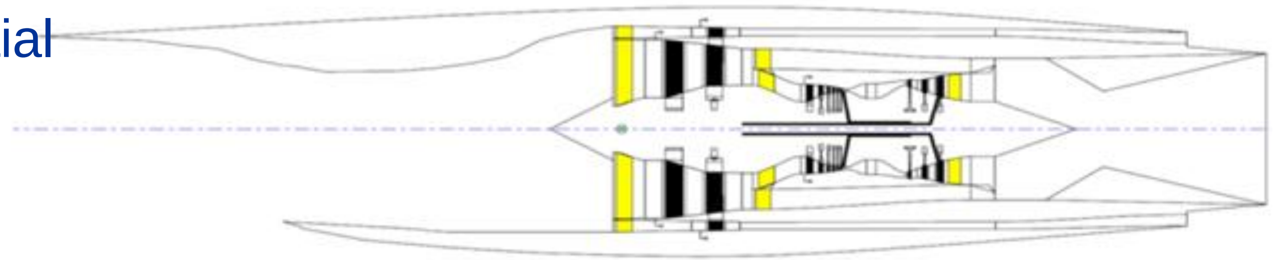




Variable Cycle Propulsion System Studies

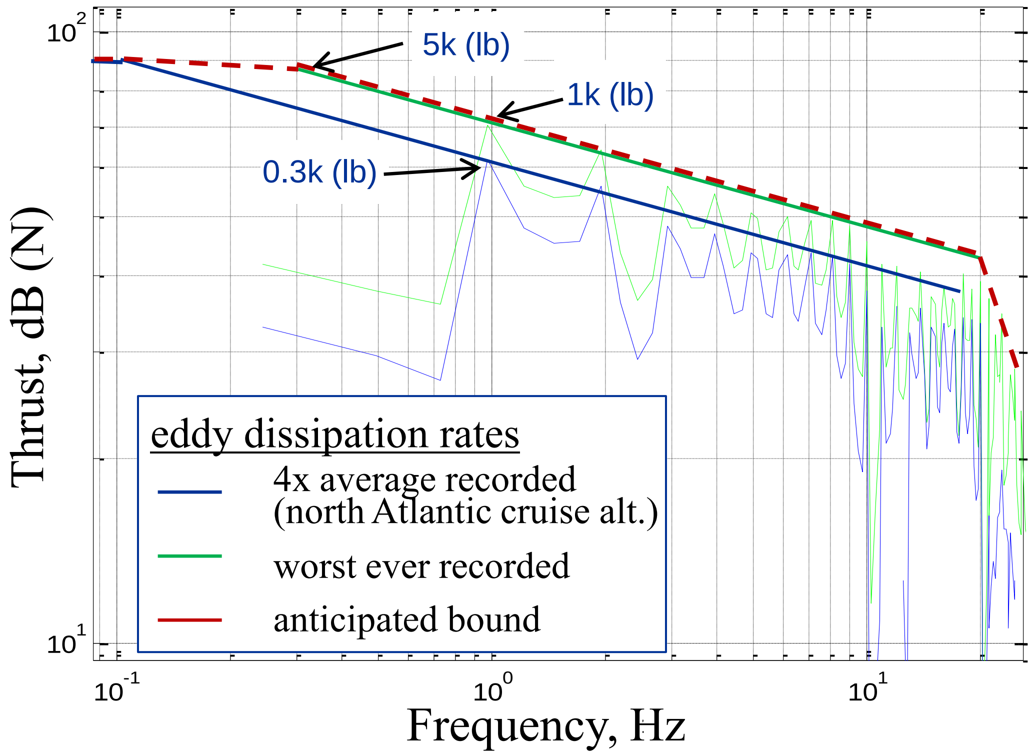
Preliminary - Thrust Spectral for Coupling to AeroServoElastic (ASE) Modes

- Study based on V1. initial variable cycle engine modeling



- Atmospheric turbulence model w/ eddy dissipation rates & momentary wind gusts up to 180 mph

- Study shows potentially significant trust dynamics to warrant detailed APSE modeling and analysis



Future

- Develop complete integrated propulsion system variable cycle engine dynamic models and control designs
- Develop Integrated APSE system models, integrated vehicle controls, and conduct APSE studies
- Close integration between NPSS and APSE (already started)

Additional Possibilities of this Research

- Integrate w/ NPSS to develop a complete cycle deck design and verification package and controls development platform/Rig

- With gas dynamic model explore higher bandwidth controls to reduce stall margins and improve efficiency and design advanced controls to improve flight safety and operability